

# The Importance of Crop Residue Management in Maintaining Soil Quality in Zero Tillage Systems; A Comparison between Long-term Trials in Rainfed and Irrigated Wheat Systems

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CIMMYT is committed to improving livelihoods in developing countries by improving the productivity and profitability of farming systems while sustaining natural resources. This paper focuses on the influence of crop residue management on soil quality in zero till systems and includes results from two long-term trials established in the early 1990's in different agro-ecological systems in Mexico: (1) a low-input, semi-arid, rainfed system in the rainfed central highlands (2240 masl) with zero tillage on the flat and (2) a high-input, arid, irrigated system in the northwestern part of the country with zero tilled permanent raised beds. In both zero till systems, the (partial) retention of the crop residues was necessary to maintain soil quality. In the rainfed semi-arid zero tillage system, mean weight diameter obtained by dry sieving, aggregate stability, infiltration, soil moisture content, soil microbial biomass and nutrient status were lower with residue removal than with residue retention. In the irrigated permanent raised bed system, burning of all crop residues resulted in a degradation of soil structure, lower direct infiltration, irrigation efficiency, soil moisture content, soil microbial biomass, lower total N and greater soil sodicity as compared to retaining crop residue at the surface. Practices with partial retention of crop residue showed soil quality similar to practices with retention of all residues. The retention of at least part of the crop residue is essential for the sustainability of zero till systems, although it may be possible to remove part of the residue for other uses, especially in irrigated conditions where biomass production is high.

**Key words:** zero tillage, permanent raised bed planting, residue management, soil quality

Human efforts to produce ever-greater amounts of food leave their mark on our environment. Persistent use of conventional farming practices based on extensive tillage, and especially when combined with in situ burning of crop residues, have magnified soil erosion losses and the soil resource base has been steadily degraded (Montgomery, 2007). Nowadays, people have come to understand that agriculture should not only be high yielding, but also sustainable (Reynolds and Borlaug, 2006). Farmers concerned about the environmental sustainability of their crop production systems combined with ever-increasing production costs have begun to adopt and adapt improved management practices which lead towards the ultimate vision of sustainable conservation agriculture. Conservation agriculture addresses a concept of the complete agricultural system, combining three basic principles (1) reduction in tillage, (2) retention of adequate levels of crop residues and surface cover of the soil surface and (3) use of economically viable crop rotations. These conservation agriculture principles are applicable to a wide range of crop production systems. Obviously, specific and compatible management components will need to be identified through adaptive research with active farmer involvement for contrasting agro-climatic/production systems.

This paper includes results from two long-term trials operated by the International Maize and Wheat Improvement Centre (CIMMYT) in different agro-ecological systems in Mexico. The first experiment is located near El Batán, approximately 30 km northeast of Mexico City, in the subtropical highlands of Mexico. Rainfed cropping predominates in the area, with rainfall (350–800 mm) occurring during a four to six months summer period, followed by dry, frosty winters. The climate of El Batán makes it representative of many highland areas in the West Asia and North Africa region, the Southern Cone and Andean Highlands of South America, the central highlands of Ethiopia, the Mediterranean coastal plains of Turkey and the highlands of central Mexico. Each area has its specific conditions and problems, but some overall trends are recognisable. The tropical and subtropical highlands (central Mexico, Ethiopia, ...) have been densely populated and intensively cropped for centuries resulting in agricultural sustainability problems related to soil erosion and fertility decline (Scherr and Yadav, 1996). The agricultural system is under stress due to shrinking cultivated area per household, reduced fodder availability and land degradation (Aune et al., 2001). Rainfall is inadequate and

unpredictable, hence crop production is threatened by chronic soil moisture stress. Precipitation is usually intensive and short, leading to high runoff and temporal water logging. Cereal grain yields are low ( $<2 \text{ t ha}^{-1}$ ). Moreover, fields are often weedy and crops are N deficient, soil structure is poor, and sheet and gully erosion are widespread (Nyssen et al., 2000, 2005).

The second experiment is located in the Yaqui Valley in the arid, northwestern part of Mexico. In the Yaqui Valley over the past 25 years, more than 95% of the region's farmers have switched from using flood irrigation on the flat to planting on raised beds (Aquino, 1998). One to four rows are planted on top of the bed, depending on the bed width and crop, with irrigation applied in the furrow. Farmers growing wheat on beds obtain 8% higher yields and save nearly 25% in production costs, compared with the flood irrigation systems (Aquino, 1998). Grain yields in the area exceed  $6 \text{ t ha}^{-1}$  and input levels are high, e.g. the average N rate for wheat is  $275 \text{ kg N ha}^{-1}$ . Widespread burning of crop residues often accompanies tillage, although some residues are baled-off for fodder and incorporated during tillage (Sayre, 2004). Bed planting provides a natural opportunity to reduce compaction by confining traffic to the furrow bottoms. The next logical step to increase the sustainability of beds is to make them permanent, avoiding tillage (only reshaping the beds as needed) and retaining and distributing crop residues on the surface.

A simple operational definition of soil quality is given by Gregorich et al. (1994) as 'The degree of fitness of a soil for a specific use'. Within the framework of agricultural production, high soil quality equates to the ability of the soil to maintain high productivity without significant soil or environmental degradation. Evaluation of soil quality is based on physical, chemical and biological characteristics of the soil. Management factors that can modify soil quality include e.g. tillage and residue management systems, and sowing crop rotations (Karlen et al., 1997). This paper focuses on the influence of residue management on soil quality parameters in zero till systems. A comparison is made between conservation agriculture systems in two contrasting agro-ecological areas: (1) a low-input, semi-arid, rainfed system with zero tillage on the flat and (2) a high-input, arid, irrigated system with zero till permanent raised beds.

## Materials and Methods

### *The Rainfed Long-term Trial in Central Mexico*

The rainfed experiment is located in El Batán in the semiarid, subtropical highlands of Central Mexico (2240 m a.s.l.;  $19.3^{\circ}\text{N}$ ,  $98.5^{\circ}\text{W}$ ). The soil has good chemical and physical conditions for farming. The major limitations are periodical drought, periodical water excess and wind and water erosion. The mean annual temperature is  $14^{\circ}\text{C}$  (1990-2001) and the average annual rainfall is  $600 \text{ mm y}^{-1}$ , with approximately 520 mm falling between May and October. Short, intense rain showers followed by dry spells typify the summer rainy season and the total yearly potential evapotranspiration of 1900 mm exceeds rainfall throughout the year. The El Batán experiment station has an average growing period of 152 days. The soil is a fine, mixed, thermic Cumulic Haplustoll (Soil Survey Staff, 2003) (Cumulic Phaeozem (IUSS Working Group WRB, 2006)). The experiment was started in 1991 as described in Fischer et al. (2002). Individual plots are  $7.5 \text{ m}$  by  $22 \text{ m}$ . Standard practices include the use of recommended crop cultivars, with maize planted at  $60,000 \text{ plants ha}^{-1}$  in  $75 \text{ cm}$  rows and wheat planted in  $20 \text{ cm}$  rows at  $100 \text{ kg seed ha}^{-1}$ . Both crops are fertilized using urea at  $120 \text{ kg N ha}^{-1}$ , with all N applied to wheat at the 1st node growth stage (broadcast) and to maize at the 5-6 leaf stage (surface-banded). Weed control is done using appropriate, available herbicides as needed and no disease or insect pest controls are utilized, except for seed treatments applied by commercial seed sources. Planting of both maize and wheat depends on the onset of summer rains but is usually done between June 5 and 15.

The experimental design consists of a randomized complete block with two replications. There are 32 treatments in all. The core set of 16 management practices was based on variation of (1) crop rotation (monocropping vs. a maize/wheat rotation); (2) tillage (conventional vs. zero tillage); (3) residue management (retention vs. removal). A second set of treatments was established in 1996 and includes treatments with partial residue retention and planting on permanent raised beds. In this paper only treatments with zero tillage on the flat and crop rotation will be considered.

### *The Irrigated Long-term Trial in Northwestern Mexico*

The experiment was initiated in 1992 near Ciudad Obregón, state of Sonora, Mexico (Lat.  $27.33^{\circ}\text{N}$ , Lon.  $109.09^{\circ}\text{W}$ , 38 masl). The mean annual temperature is  $24.7^{\circ}\text{C}$  and average annual precipitation 384 mm, with 253.1 mm in a rainy season from June until August (1971-2000) (<http://www.inegi.gob.mx>). The soil is a coarse sandy clay, mixed montmorillonitic Chromic Haplotorrert (Vertisol Calcaric Chromic), low in organic matter ( $< 1\%$ ) and slightly alkaline (pH 7.7). A detailed description of plot management has been reported in Limon-Ortega et al. (2000). Wheat and maize

are irrigated and managed in an annual rotation: wheat as a winter crop planted in late November to early December and harvested in May, followed by maize as summer crop planted in June on the same whole plots and harvested in October. Both crops are planted on 0.75 m raised beds with wheat in two rows seeded 20 cm apart and maize in one row. Irrigation is applied in furrows. The experiment includes three replicates of each treatment in a randomized complete block design with a split plot treatment arrangement. Main plots consist of tillage-straw factors as follows: (1) *CTB-straw incorporated*: Conventionally tilled raised beds (conventional tillage with beds formed after each crop); wheat and maize residues are plowed under; (2) *PB-straw burned*: Permanent raised beds (zero tillage with continual reuse of existing beds, which are reformed as needed); residues of both wheat and maize are burned; (3) *PB-straw removed*: Permanent raised beds; residues of wheat and maize are removed by baling; (4) *PB-straw partly removed*: Permanent raised beds; maize residues are removed by baling and wheat straw is retained on the soil surface; (5) *PB-straw retained*: Permanent raised beds; maize and wheat residues are kept on the soil surface. Only the permanent raised bed treatments will be included in this paper.

Split plots during the winter comprise seven N fertilizer levels, but for this paper we chose a set of three N treatments (0, 150, and 300 kg N ha<sup>-1</sup>). Maize receives a uniform application of 150 kg N ha<sup>-1</sup>. The N fertilizer is applied as urea in the bottom of the furrow and incorporated through irrigation. Each year wheat and maize receive 45 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> banded in the furrow and incorporated through cultivation when reshaping beds.

### **Soil Quality Parameters**

Aggregate size distribution and stability were determined during the 2006 growing season in El Batán as described in Govaerts et al. (2006) and in Ciudad Obregón as described in Limon-Ortega et al. (2006). Time-to-pond, the time it takes before water runs-out of a specific area in the field, was measured during the 2006 growing season in El Batán and during the 2007-2008 season in Ciudad Obregón as described in detail in Govaerts et al. (2006). Small ring infiltration was determined in El Batán as reported in Govaerts et al. (2007a). Infiltration during irrigation was measured for the third auxiliary irrigation in the 2007-2008 season in Obregón. Inflow was measured with a calibrated bucket at the beginning of one furrow per main plot at regular time intervals. Outflow was monitored per main plot with a V-notch weir of 30°. Soil moisture content was determined volumetrically once a week during the 2007 season in El Batán and the 2007-2008 season to a depth of 60 cm. Soil microbial biomass C and N were measured as reported in Govaerts et al. (2007b) and Limon-Ortega et al. (2006).

## **Results and Discussion**

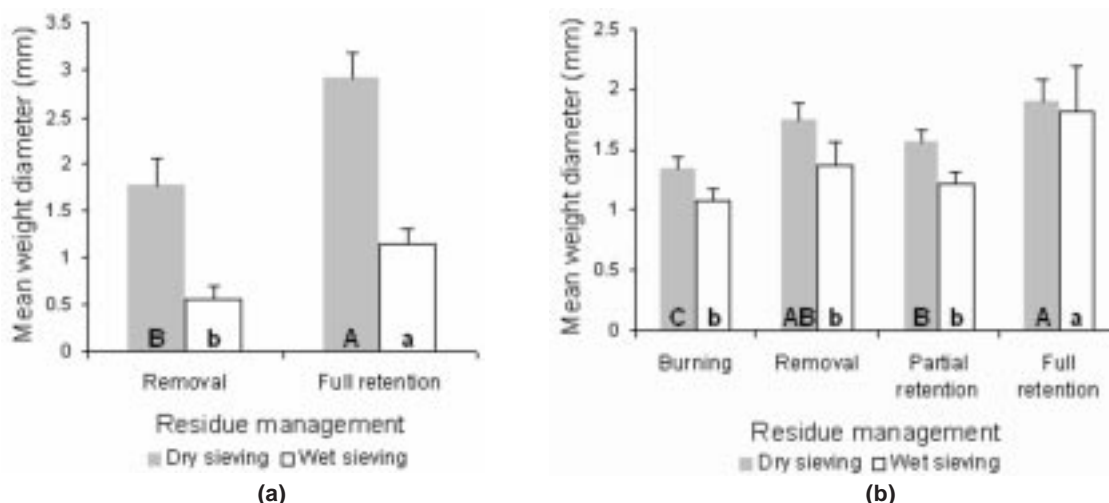
### **Soil Aggregation**

As well in the rainfed trial as in the irrigated trial, the mean weight diameter (MWD) of both dry and wet sieving was the highest when all residues were retained on the surface of the zero till fields. The removal of crop residue in rainfed conditions and the burning of residue in irrigated conditions degraded soil structure as compared to the (partial) retention of the residue (Figure 1). Chan et al. (2002) also found that stubble burning significantly lowered the water stability of aggregates in the fractions >2 mm and < 50 µm. Govaerts et al. (2007c) obtained similar results in a rainfed permanent raised bed planting system in the subtropical highlands of Mexico, where the MWD of dry and wet sieving decreased with decreasing amounts of residues retained, although partial residue removal by baling kept aggregation within acceptable limits. This indicates that total removal of residues has to be avoided, but it is not always necessary to retain all crop residues in the field to achieve the benefits of permanent raised beds or zero tillage on the flat systems. The management of previous crop residues is key to soil structural development and stability since organic matter is an important factor in soil aggregation. Fresh residue forms the nucleation centre for the formation of new aggregates by creating hot spots of microbial activity where new soil aggregates are developed (De Gryze et al., 2005). In addition, the retention of crop residue on the soil surface decreases the breakdown of aggregates by protecting them against raindrop impact (Le Bissonnais, 1996).

### **Water Infiltration**

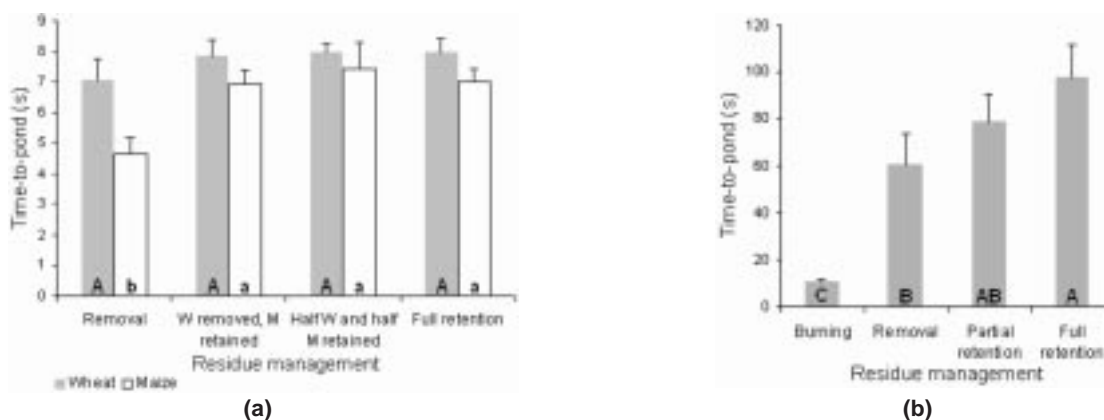
#### *Time-to-pond*

Time-to-pond is a measure for the direct infiltration in the soil. In the rainfed trial, time-to-pond was lower for zero tillage with removal of residue than with (partial) residue retention, but the difference was only significant in the maize



**Figure 1.** The effect of residue management on mean weight diameter obtained by dry and wet sieving (mm) in the zero till treatments of (a) the rainfed trial in El Batán and (b) the irrigated trial in Ciudad Obregón (Adapted from Limon-Ortega et al. 2006). Values with different letters differ significantly at 5% based on least square difference grouping. Bars indicate standard error.

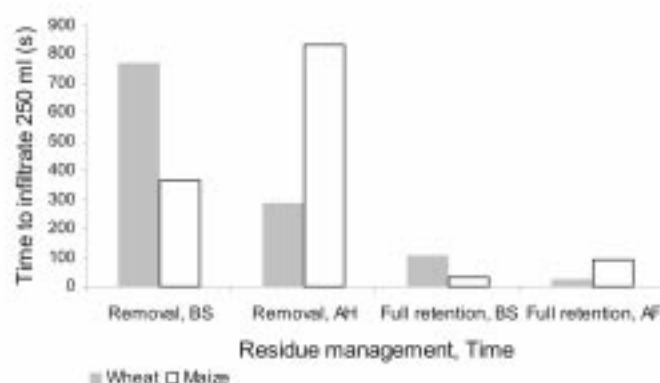
phase of the rotation (Figure 2). In plots with wheat time-to-pond was higher than in plots with maize and differences between treatments were smaller. The standing crop induces a 'vertical' mulching effect that is smaller in maize plots since plant density is lower. In irrigated conditions, time-to-pond increased with increasing retention of residue at the soil surface. Burning of residue resulted in the lowest direct infiltration (Figure 2). The retention of crop residue at the surface prevents surface crust formation by increasing aggregate stability compared to zero tillage with residue removal or burning (Figure 1; Li et al. 2007; Chan et al. 2002) and protecting aggregates from direct raindrop impact (Le Bissonnais 1996). In addition, the residues left on the top soil with zero tillage and crop retention act as a succession of barriers, reducing the runoff velocity and giving the water more time to infiltrate. The residue intercepts rainfall and releases it more slowly afterwards (Scopel and Fideling 2001).



**Figure 2.** The effect of residue management on time-to-pond (s) in the zero till treatments of (a) the rainfed trial in El Batán during the maize and wheat phase of the rotation and (b) the irrigated trial in Ciudad Obregón during the wheat phase of the rotation. Values with different letters differ significantly at 5% based on least square difference grouping. Bars indicate standard error.

#### Small Ring Infiltration in Rainfed Conditions

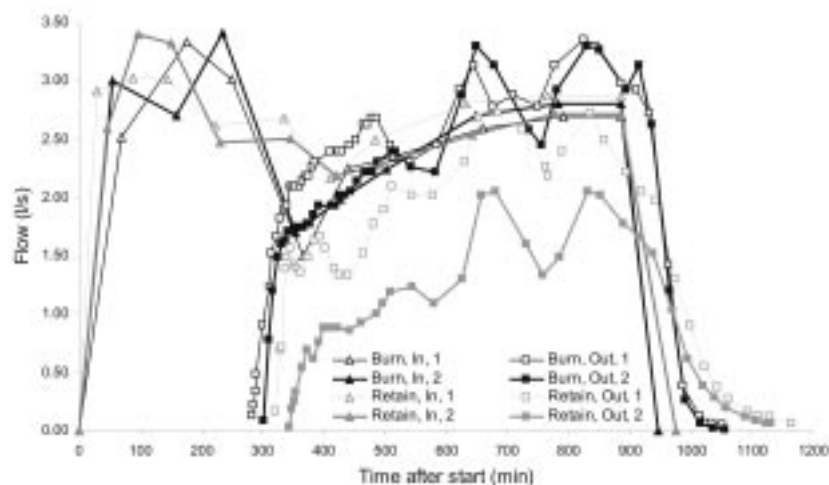
The small ring infiltration measurements in the rainfed trial showed similar results than the time-to-pond. When residue was removed, the time to infiltrate a volume of 250 ml was higher than when residue was retained, before sowing as well as after harvest (Figure 3). The retention of residue stimulates biological activity by earthworms, increasing the connectivity of macropores, an important factor in infiltration (McGarry et al., 2000).



**Figure 3.** The effect of residue management on the time (s) needed to infiltrate 250 ml of water in the zero till treatments of the rainfed trial in El Batán during the wheat and maize phase of the rotation (Adapted from Govaerts et al. 2007a) with *BS* before sowing and *AH* after harvest.

### *Infiltration during Irrigation*

In irrigated conditions, the permanent raised beds where residue was burned had an irrigation water outflow that became equal or higher than the irrigation water inflow approximately 6 hours after initiating the irrigation. In contrast, for permanent raised beds where residue was retained at the soil surface the outflow remained lower than the inflow during the whole irrigation (Figure 4). Outflow started sooner where residue was burned than where it was retained, reflecting the faster advance of water in the burned treatment. An increased advance of the water in the furrows will reduce the time for infiltration. Similarly, outflow stopped sooner when the irrigation was stopped where residue was burned than where it was retained (Figure 4). This resulted for permanent raised beds with residue burned in a very low average irrigation efficiency of 24% compared to 52% for permanent raised beds where residue was retained. The low infiltration with residue burning is related to the low aggregate stability in this practice compared to residue retention (Figure 1). The reduction infiltration might be enhanced by the reduced cracking with burning compared to retention (data not shown), since the cracks may be important pathways for infiltration in these heavy clay soils.

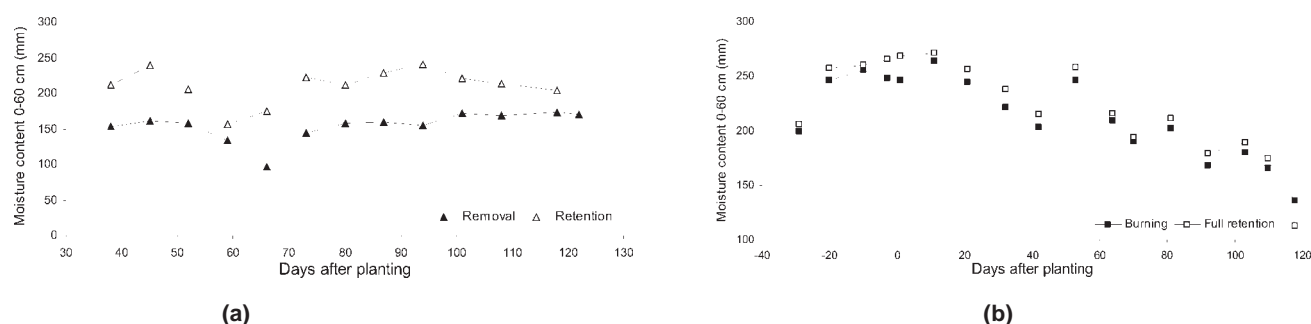


**Figure 4.** The effect of residue management on infiltration and outflow of irrigation water in the zero till treatments of the irrigated trial in Ciudad Obregón with *In* Inflow (l/s), *Out* Outflow (l/s), *Burn* Residue burning, *Retain* Full residue retention and 1 and 2 field repetitions.

### *Soil Moisture Content*

The increased infiltration with residue retention in zero tillage systems was reflected in the soil moisture content throughout the growing season. In the rainfed trial, soil moisture content in the top 60 cm of the zero till plots was lower when residue was removed compared to when residue was retained. Similarly, in the irrigated trial, soil moisture





**Figure 5.** The effect of residue management on moisture content in the profile (0-60 cm) throughout the growing season in the wheat phase of the rotation in the zero till treatments of (a) the rainfed trial in El Batán and (b) the irrigated trial in Ciudad Obregón (irrigations 28 days before and 43, 71 and 95 days after planting).

content was lower when residue was burned than with a surface mulch cover. The difference between practices was smaller in irrigated conditions, probably due to the mitigating effect of irrigation. Also Gicheru et al. (1994) showed that crop residue mulching resulted in more moisture down the profile (0-120 cm) throughout two seasons (a short rains period and a long rains period) within 2 years than conventional tillage and tied ridges in a semi-arid area of Kenya. More soil water enables crops to grow during short-term dry periods and reduces sensitivity to drought stress of the system, which is especially important in rainfed systems.

### Microbial Biomass

Soil microbial biomass C and N decreased with decreasing amount of residue retained on the soil surface in the zero till treatments of both the rainfed and the irrigated long-term trial (Table 1). The soil microbial biomass reflects the soil's ability to store and cycle nutrients (C, N, P and S) and organic matter (Dick, 1992; Carter et al., 1999) and plays an important role in physical stabilization of aggregates (Franzluebbers et al., 1999). General suppression is also related to total soil microbial biomass, which competes with pathogens for resources or causes inhibition through more direct forms of antagonism (Weller et al., 2002). Consequently, soil microbial biomass is considered an important indicator of soil quality. The rate of organic C input from plant biomass is generally considered the dominant factor controlling the amount of microbial biomass in soil (Campbell et al., 1997). Franzluebbers et al. (1999) showed that as the total organic C pool expands or contracts due to changes in C inputs to the soil, the microbial pool also expands or contracts. The continuous, uniform supply of C from crop residue retention serves as an energy source for microorganisms.

**Table 1.** The effect of residue management on soil microbial biomass C and N (SMB C and SMB N) in the wheat phase of the rotation in the zero till treatments of the rainfed trial in El Batán (0-15 cm; Adapted from Govaerts et al. 2007b) and the irrigated trial in Ciudad Obregón (0-7.5 cm; Adapted from Limon-Ortega et al. 2006).

Trial	Residue management	SMB C (mg C kg <sup>-1</sup> soil)	SMB N (mg N kg <sup>-1</sup> soil)
Rainfed, El Batán	Removal	288 B	22 A
	Full retention	453 A	20 A
Irrigated, Cd. Obregón	Burning	540 b	22 c
	Removal	617 ab	25 b
	Partial retention	681 a	25 b
	Full retention	687 a	31 a

Values with different letters differ significantly at 5% based on least square difference grouping.

### Chemical Soil Quality

Removing crop residues is associated with a decrease in soil organic matter compared to zero tillage with residue retention (Blanco-Canqui and Lal, 2007), as observed in the rainfed trial. Despite continuous C input in the treatments with residue retention, soil organic matter did not differ from the treatment with residue removal in the irrigated trial. If soil microbial biomass is used as an early indicator of soil organic matter, however, the same trend can be expected in irrigated conditions. In the rainfed trial, removal of residues resulted in a lower nutrient status based on the concentration

of C, N, K and Zn, compared to retention of residues. Only the continuous wheat treatment with residue removal approached the zero tillage treatments with residue retention. In the irrigated permanent raised bed system, total N content was 1.14 times lower in when straw was burned than when straw was retained. The N-mineralization rate was similar for the treatments with straw retained and burned, but greater for the PB-straw partly removed treatment where only wheat straw was retained. This result is presumably related to the C-N ratio of the maize left on the field in PB-straw retained. It has often been reported that during the decomposition of organic matter, inorganic N can be immobilized (Zagal and Persson, 1994), especially when organic material with a large C-N ratio is added to soil. The soil sodicity and P concentration were generally greater when residues were burned compared to the other treatments. Similarly, Govaerts et al. (2007c) observed higher K, N, C and lower Na concentrations with residue retention compared to residue removal in a rainfed permanent raised bed planting system in the subtropical highlands of Mexico.

### ***Implications for Crop Production***

In the rainfed, semi-arid zero tillage system, yields were significantly and at least 50% higher with crop residue retention than with residue removal. Zero tillage treatments with partial residue removal gave yields equivalent to treatments with full residue retention (Govaerts et al., 2005). Crop performance was related to soil moisture and the related attributes infiltration, soil structure and organic matter, showing that soil moisture is the main limiting factor of the system (Verhulst et al., 2008). It is therefore essential for the sustainability of any management practice developed for rainfed, semi-arid systems that soil water capture and storage are optimal. Zero tillage with removal of all crop residues resulted in low aggregation and aggregate stability, infiltration and soil moisture content and is not a sustainable management option for the semi-arid highlands. Zero tillage with residue retention will result in higher soil quality and more stable and higher yields in these systems. However, competitive demands for crop residues at farm level (e.g. for use as animal fodder, fuel, or construction material) are high in semi-arid rainfed systems and can constitute serious bottlenecks to the implementation of zero tillage with residue retention (Erenstein, 2002). More research is needed to establish minimum residue retention levels (thresholds).

In the irrigated permanent raised bed system, yield differences between management practices only became clear after 5 years (10 crop cycles), with a dramatic overall reduction in the yield for permanent raised beds where all residues had been routinely burned (Sayre et al., 2005). In contrast to rainfed low rain fall areas, in irrigated agricultural systems (at least in tropical, semi-tropical and the warmer, temperate areas), the application of irrigation water appears to 'hide or postpone' the expression of the degradation of many soil properties associated with continuous residue burning until they reach a level that no longer can sustain high yields, even with irrigation. The difference in soil moisture content between residue management practices was smaller in irrigated than in rainfed conditions due to the correcting effect of irrigation, allowing other factors such as nutrient availability to become more important than in rainfed conditions. Since biomass production is higher in irrigated conditions than in rainfed, semi-arid conditions, there is more scope for the removal of part of the crop residue for other uses. In the permanent raised bed systems where only 25 cm of standing stubble remained in the field (the removal treatment), aggregation, direct infiltration soil microbial biomass and yields remained within acceptable limits (Figure 1, 2 and Table 1; Sayre et al., 2005). Burning all residues resulted in a degradation of soil quality comparable to the removal of all residues in the rainfed semi-arid system, where almost no standing stubble was left in the field in order to simulate the conditions caused by the livestock grazing pressure that is common in these systems.

### **Conclusions**

In both zero till systems, the retention of (part of) the crop residues was necessary to maintain soil quality. In the rainfed semi-arid zero tillage system, mean weight diameter obtained by dry and wet sieving, infiltration, soil moisture content, soil microbial biomass and nutrient status were lower with residue removal than with residue retention. In the irrigated permanent raised bed system, burning of all crop residues resulted in a degradation of soil structure, lower direct infiltration, irrigation efficiency, soil moisture content, soil microbial biomass, total N and greater soil sodicity as compared to retaining crop residue at the surface. Practices with partial retention of crop residue showed soil quality similar to practices with retention of all residues. Especially under rainfed semi-arid production conditions, the best use of crop residues is to retain them in the field as part of the implementation of sound conservation agriculture technologies, although it may be possible to remove part of the residue for other uses. In irrigated conditions where biomass production is higher, there is more scope for the removal of part of the residue. More research is needed to establish minimum residue retention levels (thresholds) with positive impacts on soil quality and crop production.

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